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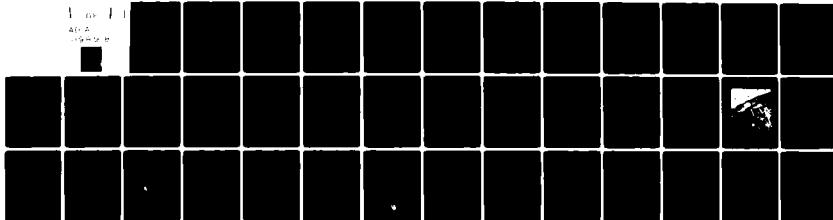
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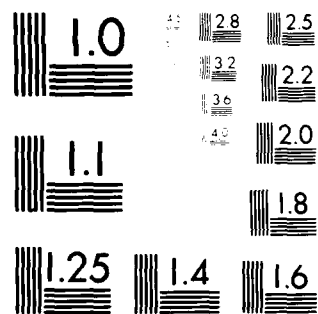
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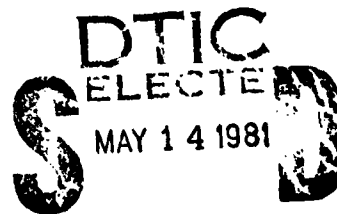
STRUCTURES NOTE 457

THE WIND SPEED SPECTRUM IN AN INDUSTRIAL ENVIRONMENT or DOES THE SPECTRAL GAP EXIST?

by

M. R. THOMSON

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(1) STRUCTURES NOTE 457

(6) **THE WIND SPEED SPECTRUM
IN AN INDUSTRIAL ENVIRONMENT
or
DOES THE SPECTRAL GAP EXIST?**

by

(10) M. R. THOMSON

(11) Oct 79

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SUMMARY

A wind speed energy density spectrum between frequencies of 0.0024 and 1800 cycles per hour is presented, together with other statistics of wind speed variation in an industrial environment. This spectrum has a much better resolution than any previously reported because the entire spectrum is based on a complete year's data sampled once per second. Comparison of these statistics with results given in the literature from research in open areas shows general agreement in the high frequency range (periods less than one day). The 12 and 24 hour period peaks in the spectrum are much better defined than in previously reported work and there is much less energy associated with periods greater than one day. The spectral gap does exist, but is much less pronounced than that in Van der Hoven's spectrum.

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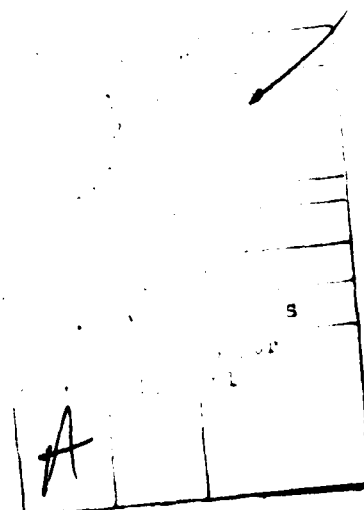
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ABSTRACT

A wind speed energy density spectrum between frequencies of 0.0024 and 1800 cycles per hour is presented, together with other statistics of wind speed variation in an industrial environment. This spectrum has a much better resolution than any previously reported because the entire spectrum is based on a complete years data sampled once per second. Comparison of these statistics with results given in the literature from research in open areas shows general agreement in the high frequency range (periods less than one day). The 12 and 24 hour period peaks in the spectrum are much better defined than in previously reported work and there is much less energy associated with periods greater than one day. The spectral gap does exist, but is much less pronounced than that in Van der Hoven's spectrum.

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1. INTRODUCTION

The "spectral gap" is the name given to the broad minimum which has sometimes been found in power spectra of wind speed between frequencies of 0.5 and 30 cycles per hour. It was first remarked upon by Van der Hoven (1957) and since then by many others (Oort and Taylor (1969), Fiedler (1970) and Vinnichenko (1970), to name a few). Some of these spectra are shown in Figure 1. However most researchers have computed the spectrum over a large frequency band by computing small parts of the spectrum from data collected over different times and with differing sample rates, and "adding" the results together. As pointed out by Bretherton *et al.* (1969) and others, it is possible for the results to be biased by this form of data selection. If the short duration records used to define the high frequency part of the spectrum are unrepresentative of the records used for the lower frequencies, then a spectral gap could be "introduced".

In this work a spectrum of wind speed is presented which uses a complete year's wind speed data to compute the spectrum over the entire frequency band.

2. EXPERIMENTAL PROCEDURE

2.1 Site of the Experiment

The anemometers used in the experiment were situated at the Aeronautical Research Laboratories (ARL) which is in an industrial area, with the general height of the crests of the surrounding roofs being about 11 metres. One of the anemometers (hereafter called anemometer A) was sited on the end of a building at a height of 14 metres above the ground and 2 metres above the crest of the roof. The second anemometer (anemometer B) was situated 9 metres above the ground in a wide gap between two buildings. Both buildings are between 9 and 12 metres in height and anemometer B was 90 metres from the edge of the nearer building, where anemometer A was situated. A site plan is shown in Figure 2. A high deciduous tree near anemometer A may have caused air flow disturbance when the wind direction was from the North.

2.2 The Anemometers

The anemometers used were a three cup variety. The cups were made by Casella and Co Limited and their light weight aluminium design gave a response length of one metre. The wind speed was determined using a light chopper technique consisting of a disc containing 24 small holes around its circumference placed on an aluminium shaft, a small lamp on one side and a photocell on the other. As the disc rotated the interruptions of the light beam created a string of pulses whose number was proportional to the number of revolutions of the cups. These pulses were amplified before being sent to the recording station. The anemometers were calibrated in the C.S.I.R.O. Division of Meteorological Physics wind tunnel and a copy of the calibration curve is shown in Figure 3. This figure shows that, except for wind speeds below about 2 m/s, the anemometers respond linearly.

The advantage of using this type of anemometer is that electrical noise and small variations in the voltage level delivered to the anemometer do not effect the output.

2.3 The Recorder

The pulses from the anemometer were electronically counted over a one second period and the resulting count was recorded on an incremental magnetic tape recorder. This recorder could

store approximately one week of data before the magnetic tape had to be changed. The pulses from the anemometer were also fed through a pulse frequency to voltage converter and recorded on a slow moving analogue paper trace recorder. A schematic diagram of the system is shown in Figure 4.

2.4 Data Error Checking

Using the ARL PDP-10 Computer each magnetic tape was checked for errors. As it was not practical to plot or print every datum point, a system was developed which plotted the maximum, minimum and mean values over a period of six minutes (corresponding to one block of data on the magnetic tape). A typical time history of these parameters for 2 anemometers is shown in Figure 5.

All plots were inspected by eye and any unusual event was cross checked with the corresponding slow moving analogue trace. If the two recorders did not agree the data were deleted and a break was made in the continuous recording. This method ensured that each file on the newly created magnetic tape consisted of an error-free continuous record of wind speed sampled once per second.

2.5 Recording Times

After some trials in January and February 1971, the experiment commenced on 1st March 1971 with Anemometer A connected. Other than two major equipment malfunctions which stopped data acquisition for periods of one week each, the recorder ran continuously for a period of one year (except for 10 minute breaks each week required to change the magnetic tape). Minor malfunctions, especially a large number of failures in the mains power supply late in 1971, caused some data loss. However, after all data found to be in error (using the method described above) were deleted, 93% of the wind speed data for every second of the year were recorded. These data values were placed on 8 magnetic tapes in 143 separate runs for analysis. The absolute times of start and stop of each run were determined with an accuracy generally better than two minutes, although in about six cases of power failures the accuracy was somewhat poorer. The best estimate of these start and stop times is shown in Table 1.

In the period July to October 1972 continuous data recording using both anemometers was made.

The daily charts from the Dynes anemometer and wind vane were obtained for the month of July 1972 from the Bureau of Meteorology equipment at Laverton RAAF Base which is situated approximately 10 km west of ARL.

3. METHOD OF ANALYSIS

3.1 Energy Spectra of Wind Speed

Because of computer storage limitations the energy spectrum of the wind speed was computed over four separate frequency ranges, but using all available data for each range. For each range the appropriate data set was divided into segments, the energy spectrum of each segment obtained and the average of the spectra for the various segments computed.

The energy spectra over the high frequency range (30 cycles per hour to 1800 cycles per hour) were computed using a 2048 point fast Fourier transform on all the data after the mean and linear drift had been removed from each set of 2048 points. The fast Fourier transform routine used was developed in 1968 using the Gentleman and Sande (1966) modification of the Cooley and Tukey (1965) technique. The individual spectra computed in this way were added together to form the energy spectrum for the year. A correction for the method of integration inherent in the manner of data collection (summation of pulses each second) was then applied to the spectrum. (See Appendices for details of the theoretical derivations used in the computation of the power spectra and integration correction.)

To extend the frequency range over which the energy spectrum of the wind speed could be computed, the data were digitally filtered (using a 256 point overlapping filter) and every 60th point was selected for further analysis. Thus a smoothed wind speed record with a sampling interval of one minute was obtained. Fourier transforms using 1024 and 4096 points were then applied to this data. (The breaks in data recording decreased the number of data values available for use in the 4096 data point case.)

To extend the frequency range yet further, the times between each data run where no data was available were padded with the appropriate number of mean values and the padded data were averaged over six data values giving a smoothed wind speed record with a sampling interval of six minutes. A 16384 point Fourier transform was then made on the resulting time series. (At the time of the analysis a 16384 point transform was the largest that could be computed on the ARL Computer.)

To obtain the overall energy spectrum, the four spectra obtained above were edited and placed on the same graph. No attempt was made to align the individual spectra by moving them relative to one another.

Using this method of analysis all the data are used in computing the spectrum over the whole frequency range. A summary of the parameters used in this analysis is given in Table 2 and the resulting energy spectrum is shown in Figure 6. The shaded area on the bottom of the graph indicates the size of the 98% confidence band.

The data from anemometer A were used in determining the spectrum. As it was possible that this anemometer was subject to local shielding a crude check was made using anemometer B. During the month of July 1972, the direction data from Laverton were used to find the difference in wind speeds measured by anemometers A and B as a function of wind direction during periods of steady wind direction. These results showed that for wind directions between 200 degrees and 60 degrees through North no consistent differences were apparent. Wind directions outside this range did not occur in the study month, nor are they common at other times.

3.2 Energy Spectra as a Function of Time of Day and Month of Year

Energy spectra were computed from the original data using a 2048 point Fourier transform. The computed spectra were classified according to time of day (in three hour periods) and month of year. To make the classification easier, the spectra were computed every 30 minutes (1800 data points) by overlapping 248 data points for every 2048 values. Over the year 96 spectra representing 8 times of day for each of the 12 months of the year were obtained and examples are shown in Figure 7. These spectra define the energy of the wind between 10 and 1000 cycles per hour.

Using the logarithm of energy spectra as the ordinate and the logarithm of the frequency as abscissa, a third order curve was fitted to each spectrum and the frequency where the gradient of the curve was equal to -1 was determined. This frequency (n_m) is the upper turnover frequency of the 'spectral gap', i.e. the frequency at which the slope of a $n \cdot P(n)$ versus $\log(n)$ plot is zero, and $n \cdot P(n)$ is a maximum. The fitted curves for the month of March 1971 and for the totals of all months are superimposed on the plotted spectra in Figure 7. The turnover frequency and spectral magnitude at this frequency for all months are given in Table 3, together with values of the mean and standard deviation of the wind speed for each period.

3.3 Energy Spectra as a Function of Wind Speed

The energy spectra computed over each 30 minute period (see Section 3.2) were divided into four classes according to the average wind speed in that 30 minute period. The resulting spectra are shown in Figure 8.

3.4 Probability Distribution of the Wind Speed

A histogram of 1-second average wind speed probability using 50 wind speed categories and the whole years data was computed, as well as a count of the number of upcrossings of

each wind speed level. These results are given in Table 4 and, together with the Raleigh Distribution computed from the mean and variance of the wind speed over the whole year, are plotted in Figure 9.

The joint distribution of wind speed versus wind speed increment over a one second interval was also computed and is shown in Figure 10.

3.5 Other Statistical Calculations

The "gustiness factor" or the ratio of the mean to the standard deviation of the wind speed is often used as a measure of the variability of the wind. The mean and standard deviation of each six minutes of data were calculated and the results placed in a joint probability histogram. Contour curves of equal probability were then drawn and are shown in Figure 11.

4. RESULTS AND DISCUSSION

4.1 Energy Spectra between 0.0024 and 1800 Cycles per Hour

Using the method described in the previous sections, the energy spectrum of the wind speed was determined and the result is shown in Figure 6. The "Spectral Gap" (the minima in the curve around frequencies of 3 cycles per hour) can be clearly seen, although it is not as marked as in Van der Hoven's spectrum (see the comparison in Fig. 12), where the "turbulence" peak centred around 1 cycle per minute, is much stronger.

The only other spectral peaks of significance as determined by the 98% confidence limits are the 12 hour and 24 hour peaks. Both these peaks have been found by other researchers (see Fig. 1). The relative amounts of power at the two frequencies seem to vary but the explanation for the variation is not obvious. Van der Hoven (using data from 75 to 125 metres above ground level) found a 12 hour peak but no significant 24 hour one. Oort and Taylor (1969) did however observe a 24 hour peak as well as a small 12 hour one, using data from 10 to 25 metres above the ground. Feidler (1970) observed the same result at 50 metre and Vinnichenko (1970) reports a strong 24 hour peak from data recorded in the free atmosphere.

The 12 and 24 hour peaks have a higher value in the spectrum reported here than in any of the others. The very small bandwidth used in computing the spectrum allows each frequency to be very accurately defined. The other spectra have as much energy in the regions about their peaks but due to their larger bandwidth this energy is slurred to adjacent frequencies.

In the lower frequency area (period greater than one day) the other spectra have a much greater energy than the spectra reported here. Differences of mean wind speed and variance explain part of the difference, although it is hard to define these parameters for a spectrum which has been pieced together from different records.

4.2 Energy Spectra as a Function of Time of Day and Month of Year

The high frequency (periods between 2 seconds and 10 minutes) spectra were computed for eight times of day (three hourly) and for each of the 12 months of the year. Some typical results are shown in Figure 7. A peak is evident in all spectra at a frequency between 25 and 125 cycles per hour. The frequency at which the peak occurred was determined by fitting a third order curve to the logarithm of the energy density versus the logarithm of the frequency curves and equating the slope of the fitted curve to -1.

The frequency of the peak found by this method was found to correlate well with the energy density of the peak frequency (see Fig. 13). Kaimal *et al.* (1972) gave a general expression for the power spectra of various atmospheric parameters, including wind velocity, over this frequency band from data collected in open areas. Using this formula it can be shown (see Appendix 3) that the frequency, n_m , of the peak and the energy, $P(n_m)$, at this peak should be related by

$$\text{Log}[P(n_m)/\sigma^2] = \text{Log}[n_m] + \text{Constant.}$$

For the frequencies calculated in this note the line of best fit between $\log[P(n_m)/\sigma^2]$ and $\log[n_m]$ has a slope of -0.94 with a correlation coefficient of 0.97 .

Although there is agreement with Kaimal *et al.* in the relation between $P(n_m)$ and the peak frequencies, the shape of the spectra does not agree at high frequencies, where the spectral energy tends toward (frequency)⁻² instead of the more usual (frequency)^{-5/3}. This may be due to the use of wind speed data in this analysis instead of velocity component data used by Kaimal *et al.*

When the frequency of the maxima is reduced to nondimensionalised units, $n_m z/U$, (see Appendix 3 for definition), there is a considerable but regular variation throughout both time of day and month of year (see Fig. 14). A summary of the calculated values of mean, standard deviation, frequency of peak (n_m) and some other derived results as a function of time of day and month of year is given in Table 3.

4.3 Energy Spectra as a Function of Wind Speed

Figure 8 shows the results of computing wind speed spectra classified by half hour mean wind speed. By ignoring the high frequency aliasing "tails" and shifting each graph in the X and Y directions as suggested by Kaimal *et al.* a collapse to one graph occurs.

4.4 Wind Speed Probability Distribution

The results of the wind speed probability distribution analysis are shown in Figure 9. One of the curves shown is the wind speed distribution curve. It is known (see e.g. Hasofer, 1970 or Davenport, 1967) that during periods when the wind is a stationary, gaussian turbulent process the wind speed has a Rayleigh distribution. Over a long time period the wind is not a stationary process. The second curve in Figure 9 shows the Rayleigh distribution which best fits the wind speed probability density. The two curves differ considerably, especially at the higher wind speeds.

The number of upcrossings of various levels by a random process depends on the joint probability density of the process and its derivative. (See e.g. Sherman and Thomson, 1972.) If the process and its derivative are statistically independent, the number of upcrossings of any level is proportional to the probability density at that level. Figure 9 shows, as a third curve, the upcrossings of the wind speed process. This curve differs from the observed wind speed distribution at low wind speeds. Figure 10 shows the joint distribution of wind speed and its derivative. The two variables are not independent for the long term (non-stationary) record. This might have been expected *a priori*, for the high wind speed derivatives are more likely to occur during periods of high mean wind speed, when high instantaneous wind speeds are also more likely.

4.5 Gustiness Factor

The final statistical analysis reported here is the calculation of the gustiness factor or the ratio of the mean to the standard deviation of the wind speed. Figure 11 shows a joint distribution of the six minute means and standard deviations over the whole year. The mean and the standard deviation are correlated, but there is considerable scatter of the points, so gustiness factor may only be used as a crude indicator of possible errors in wind speed data.

5. CONCLUSIONS

The wind speed spectrum reported here does show a spectral gap, but the effect is not nearly as pronounced as in Van der Hoven's spectrum because the energy at frequencies above 10 cycles/hour is relatively much less. Otherwise the results reported in this note suggest that the wind speed energy spectrum in the ARL environment differs from some other reported wind speed spectra, in that there is:

1. A lower mean wind speed which reduces the variance of the wind speed signal and so the whole spectrum is lowered.

2. Relatively less energy in the periods greater than one day.

3. A very much larger peak at both 12 and 24 hour periods. This is due to the very narrow bandwidth used in computing the spectrum.

The high frequency region of the spectrum is in general agreement with other reported spectra.

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APPENDIX 1

Definitions of Power Spectral Terminology Used in the Text

The definitions of Fourier Transform and Power Spectra are:

Fourier Transform for the case of a finite number of equally spaced data values (Discrete Fourier Transform) is given by

$$\hat{X}_m = \frac{1}{N} \sum_{r=0}^{N-1} X_r e^{j \frac{2\pi m r}{N}} \quad \text{for } m = 0 \text{ to } N-1$$

where

X_r is the r th data value

j is $\sqrt{-1}$

N is total number of data points

\hat{X}_m is the m th estimate of the Fourier Transform.

The frequency corresponding to the Fourier transform estimate \hat{X}_m is

$$n_m = \frac{m \times f_R}{N} \quad \text{for } m = 0 \text{ to } N-1$$

where

f_R is the reading frequency $= 1/\Delta t$

Δt is the time increment between each data value.

The inverse Fourier transform is defined as

$$X_r = \sum_{m=0}^{N-1} \hat{X}_m e^{-j \frac{2\pi m r}{N}} \quad \text{for } r = 0 \text{ to } N-1$$

The Power Spectra is defined as

$$P_m = K X_m^* X_m \quad \text{for } m = 0 \text{ to } N-1$$

where

\hat{X}_m is the m th estimate of the Fourier transform

\hat{X}_m^* is its complex conjugate.

The constant K is defined such that

$$\sum_{m=0}^{N-1} P_m \Delta n = \sigma^2$$

where

Δn is the frequency increment $= f_R/N$

σ^2 is the variance of the data values

with this definition

$$K = \frac{2}{\Delta n} = \frac{2N}{f_R}$$

The 98% confidence bands of a power spectrum are

$$\text{upper limit} = 14.3 \times \left(\frac{2}{3k-1} + \frac{1}{\sqrt{k-1}} \right) db$$

$$\text{lower limit} = 14.3 \times \left(\frac{2}{3k-1} - \frac{1}{\sqrt{k-1}} \right) db$$

where k is the number of statistical degrees of freedom

$k = 2N/m$ where N is the total number of data points used,
 m is the number of spectral estimates obtained.

APPENDIX 2

The Effect of Time Averaging on the Power Spectra

When winds are measured by recording the wind run over a time interval a smoothing process is involved which affects the high frequency end of the spectrum.

Let Y_m be the m th data value obtained by averaging the wind run over a period Δt commencing at time $m\Delta t$ then

$$Y_m = \frac{1}{\Delta t} \int_{m\Delta t}^{(m+1)\Delta t} X(t) dt$$

where $X(t)$ is the actual continuous wind speed function.

If the recording is made over time T then

$$N \Delta t = T$$

where N is the number of averaged wind speed estimates.

The Fourier series transform of the continuous wind speed function over this time is

$$G(n) = \frac{1}{T} \int_0^T X(t) e^{-\frac{2\pi i n t}{T}} dt$$

and the inverse transform is

$$X(t) = \sum_{n=-\infty}^{\infty} G(n) e^{-\frac{2\pi i n t}{T}}$$

The Fourier series of the averaged wind speed estimates is

$$\begin{aligned} A_s &= \frac{1}{N} \sum_{m=0}^{N-1} Y_m e^{-\frac{2\pi i m s}{N}} \\ &= \frac{1}{N} \sum_{m=0}^{N-1} \frac{1}{\Delta t} \left[\int_{m\Delta t}^{(m+1)\Delta t} X(t) dt \right] e^{-\frac{2\pi i m s}{N}} \\ &= \frac{1}{N} \sum_{m=0}^{N-1} \frac{1}{\Delta t} \left[\int_{m\Delta t}^{(m+1)\Delta t} \sum_{n=-\infty}^{\infty} G(n) e^{-\frac{2\pi i n t}{T}} dt \right] e^{-\frac{2\pi i m s}{N}} \\ &= \frac{1}{N\Delta t} \sum_{n=-\infty}^{\infty} G(n) \sum_{m=0}^{N-1} e^{-\frac{2\pi i m s}{N}} \int_{m\Delta t}^{(m+1)\Delta t} e^{-\frac{2\pi i n t}{T}} dt \\ \therefore A_s &= \frac{1}{N\Delta t} \sum_{n=-\infty}^{\infty} G(n) \sum_{m=0}^{N-1} e^{-\frac{2\pi i m s}{N}} T e^{-\frac{2\pi i n m \Delta t}{T}} \left(e^{-\frac{2\pi i n \Delta t}{T}} - 1 \right) \\ &= \frac{T}{N\Delta t} \sum_{n=-\infty}^{\infty} G(n) \left[\frac{e^{-\frac{2\pi i n \Delta t}{T}} - 1}{-2\pi i n} \right] \sum_{m=0}^{N-1} e^{-\frac{2\pi i m s}{N}} e^{-\frac{2\pi i n m \Delta t}{T}} \\ &= \frac{N\Delta t}{N\Delta t} \sum_{n=-\infty}^{\infty} G(n) \left[\frac{e^{-\frac{n\Delta t}{T}} \left(e^{-\frac{n\Delta t}{T}} - e^{-\frac{n\Delta t}{T}} \right)}{-2\pi i n} \right] \sum_{m=0}^{N-1} e^{-\frac{2\pi i m}{N} (s - n)} \\ &= \sum_{n=-\infty}^{\infty} G(n) e^{-\frac{2\pi i n s}{T}} \frac{\sin \left(\frac{\pi n \Delta t}{T} \right)}{\pi n} \cdot N \cdot \delta(s - n) \end{aligned}$$

$$\text{as } \delta(r) = \frac{1}{N} \sum_{m=0}^{N-1} e^{\frac{2\pi i m r}{N}}$$

$$\therefore A_s = G(s) e^{\frac{2\pi i s \Delta t}{T}} \cdot \frac{\pi s \Delta t}{T} \cdot \text{Sin}\left(\frac{\pi s \Delta t}{T}\right)$$

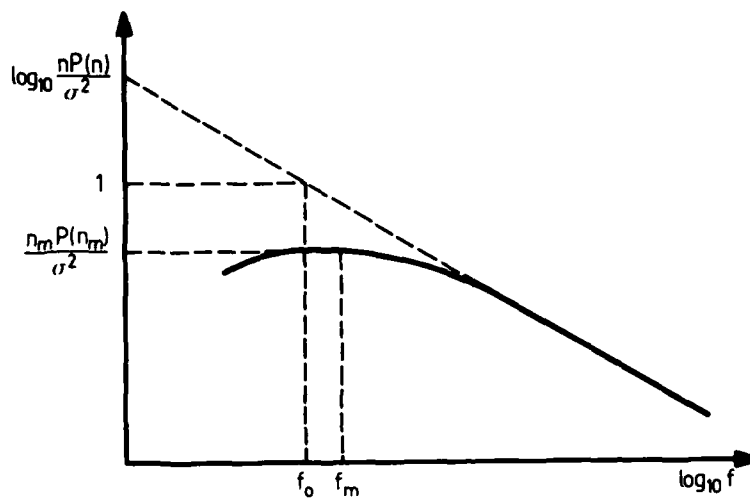
$$\text{and Power Spectra} = A_s^* A_s$$

$$= G^*(s) G(s) \left[\frac{\text{Sin}\left(\frac{\pi s \Delta t}{T}\right)}{\frac{\pi s \Delta t}{T}} \right]^2$$

$$\therefore \text{Power Spectra of averaged data}$$

$$= \text{Power Spectra of continuous data} \times \left(\frac{\text{Sin}\left(\frac{\pi s \Delta t}{T}\right)}{\frac{\pi s \Delta t}{T}} \right)^2$$

APPENDIX 3



n frequency (in cycles/hour)

$P(n)$ Power Spectral Density

U mean wind velocity

σ^2 variance at wind velocity

z vertical height.

Subscript m value at turnover point

Subscript o value when

$$\text{Log}_{10} \frac{nP(n)}{\sigma^2} = 1$$

From Kaimal *et al.*

$$\frac{nP(n)}{\sigma^2} = \frac{0.16 (f/f_0)}{1 + 0.16 (f/f_0)^{5.3}} \text{ and } f = \frac{nz}{U}$$

to find the turnover point differentiate with respect to f

$$f = f_m = \left(\frac{3}{2 \times 0.16} \right)^{3.5} f_0$$

and

$$\frac{n_m P(n_m)}{\sigma^2} = 0.16 \left(\frac{3}{2 \times 0.16} \right)^{3.5} = \text{Constant.}$$

$$\therefore \text{Log}_{10} \frac{P(n_m)}{\sigma^2} = -\log_{10}(n_m) + \text{Constant.}$$

TABLE 1
Files of Error-free Wind Speed Data

File No.	Start of File				Length Secs.	End of File			
	Y	D	H	M		Y	D	H	M
1	71	19	2	15	6840	71	19	4	9
2	71	19	4	19	93960	71	20	6	25
3	71	21	0	0	277560	71	24	5	6
4	71	24	5	6	85680	71	25	4	54
5	71	25	4	54	88920	71	26	5	36
6	71	26	5	36	135360	71	27	19	12
7	71	49	7	6	79560	71	50	5	12
8	71	50	5	12	175320	71	52	5	54
9	71	52	5	54	134280	71	53	19	12
10	71	53	19	12	99360	71	54	22	48
11	71	57	1	35	19440	71	57	6	59
12	71	59	23	6	351720	71	64	0	48
13	71	64	2	0	413280	71	68	20	48
14	71	68	23	36	197280	71	71	6	24
15	71	71	7	0	504000	71	77	3	0
16	71	77	7	22	89640	71	78	8	16
17	71	78	9	10	227520	71	81	0	22
18	71	81	1	16	275400	71	84	5	46
19	71	84	6	15	563040	71	90	18	39
20	71	91	6	14	87480	71	92	6	32
21	71	92	6	38	131040	71	93	19	2
22	71	93	19	8	301320	71	97	6	50
23	71	97	6	56	77040	71	98	4	20
24	71	98	5	0	602640	71	105	4	24
25	71	105	4	38	300240	71	108	16	2
26	71	108	16	8	312480	71	112	6	56
27	71	112	7	11	583200	71	119	1	11
28	71	119	1	22	236160	71	121	18	58
29	71	121	19	52	365400	71	126	1	22
30	71	126	1	20	172440	71	128	1	14
31	71	128	6	14	343440	71	132	5	38
32	71	132	6	32	67680	71	133	1	20
33	71	133	1	33	236520	71	135	19	15
34	71	135	22	51	357840	71	140	2	15
35	71	141	0	56	539280	71	147	6	44
36	71	147	6	58	176400	71	149	7	58
37	71	149	8	6	57960	71	150	0	12
38	71	150	0	20	201960	71	152	8	26
39	71	152	8	34	28800	71	152	16	34
40	71	152	16	42	44640	71	153	5	6
41	71	153	5	36	39600	71	153	16	36
42	71	154	5	36	16920	71	154	10	18
43	71	154	10	40	86040	71	155	10	34

Foot Note Y = Year

D = Day of year

H = Hour of Day

M = Minute

Times are Greenwich Mean Times Local (Eastern Standard) time = GMT + 10 Hours.
Data in Files 12 to 154 were used in the analysis.

TABLE 1—(Continued)

File No.	Start of File				Length Secs.	End of File			
	Y	D	H	M		Y	D	H	M
44	71	155	10	42	102600	71	156	15	12
45	71	156	15	20	158400	71	158	11	20
46	71	158	11	28	18000	71	158	16	28
47	71	158	19	58	122040	71	160	5	52
48	71	160	11	22	44280	71	160	23	40
49	71	161	6	21	603360	71	168	5	57
50	71	168	6	25	152640	71	170	0	49
51	71	179	6	25	86760	71	180	6	31
52	71	180	6	37	78120	71	181	4	19
53	71	181	4	27	5400	71	181	5	57
54	71	181	6	40	37800	71	181	17	10
55	71	181	18	4	558720	71	188	5	16
56	71	188	5	45	84600	71	189	5	15
57	71	189	5	21	89280	71	190	6	9
58	71	190	6	15	49680	71	190	20	3
59	71	190	20	57	150480	71	192	14	45
60	71	192	14	51	55440	71	193	6	15
61	71	193	6	21	126360	71	194	17	27
62	71	194	18	21	30600	71	195	2	51
63	71	195	3	15	14760	71	195	7	21
64	71	195	7	27	87840	71	196	7	51
65	71	196	7	57	214920	71	198	19	39
66	71	198	21	9	52920	71	199	11	51
67	71	199	14	21	18720	71	199	19	33
68	71	199	19	41	60120	71	200	12	23
69	71	200	12	31	76320	71	201	9	43
70	71	201	11	13	64080	71	202	5	1
71	71	202	5	10	292680	71	205	14	28
72	71	205	17	38	303480	71	209	5	56
73	71	209	6	5	10440	71	209	8	59
74	71	209	9	53	143640	71	211	1	47
75	71	211	1	55	263520	71	214	3	7
76	71	214	3	15	10800	71	214	6	15
77	71	214	6	23	32760	71	214	15	29
78	71	214	16	23	79200	71	215	14	23
79	71	215	15	17	7920	71	215	17	29
80	71	215	18	23	26640	71	216	1	47
81	71	216	3	45	306000	71	219	16	45
82	71	219	17	13	720	71	219	17	25
83	71	219	17	53	285840	71	223	1	17
84	71	223	1	17	456120	71	228	7	59
85	71	228	8	23	158400	71	230	4	23
86	71	230	4	25	109800	71	231	10	55
87	71	231	11	3	84960	71	232	10	39
88	71	232	10	47	392040	71	236	23	41
89	71	237	3	10	236520	71	239	20	52
90	71	239	21	46	156960	71	241	17	22
91	71	241	17	30	187200	71	243	21	30

TABLE 1—(Continued)

File No.	Start of File				Length Secs.	End of File			
	Y	D	H	M		Y	D	H	M
92	71	244	3	25	513720	71	250	2	7
93	71	250	3	1	3600	71	250	4	1
94	71	250	4	55	80640	71	251	3	19
95	71	251	3	15	90720	71	252	4	27
96	71	252	5	21	506520	71	258	2	3
97	71	258	2	20	493920	71	263	19	32
98	71	263	20	26	113400	71	265	3	56
99	71	265	3	55	437040	71	270	5	19
100	71	270	5	27	124560	71	271	16	3
101	71	271	16	11	49320	71	272	5	53
102	71	272	6	0	50040	71	272	19	54
103	71	272	20	34	191880	71	275	1	52
104	71	275	1	58	338400	71	278	23	58
105	71	279	0	4	20520	71	279	5	46
106	71	279	6	5	604800	71	286	6	5
107	71	286	6	20	360	71	286	6	26
108	71	286	6	38	87120	71	287	6	50
109	71	287	7	2	518400	71	293	7	2
110	71	293	7	10	65880	71	294	1	28
111	71	294	1	40	305640	71	297	14	34
112	71	297	14	46	92880	71	298	16	34
113	71	298	16	40	134280	71	300	5	58
114	71	300	6	5	309600	71	303	20	5
115	71	303	20	23	241200	71	306	15	23
116	71	306	15	35	50040	71	307	5	29
117	71	307	5	30	601920	71	314	4	42
118	71	314	5	0	360	71	314	5	6
119	71	314	5	24	549360	71	320	14	0
120	71	320	14	12	56880	71	321	6	0
121	71	321	6	0	60840	71	321	22	54
122	71	321	23	0	90720	71	323	0	12
123	71	323	0	20	2520	71	323	1	2
124	71	323	1	8	380160	71	327	10	44
125	71	327	10	52	30960	71	327	19	28
126	71	328	5	0	70920	71	329	0	42
127	71	329	0	54	482400	71	334	14	54
128	71	334	15	6	56880	71	335	6	54
129	71	335	7	5	277560	71	338	12	11
130	71	338	12	19	133560	71	340	1	25
131	71	340	1	33	189360	71	342	6	9
132	71	342	6	11	2520	71	342	6	53
133	71	342	7	1	15840	71	342	11	25
134	71	342	11	33	369360	71	346	18	9
135	71	346	18	17	146160	71	348	10	53
136	71	349	6	15	94680	71	350	8	33
137	71	350	8	41	426240	71	355	7	5
138	71	356	7	12	9720	71	356	9	54
139	71	356	10	2	6840	71	356	11	56

TABLE 1—(Continued)

File No.	Start of File				Length Secs.	End of File			
	Y	D	H	M		Y	D	H	M
140	71	356	12	4	10800	71	356	15	4
141	71	356	15	12	10080	71	356	18	0
142	71	356	18	8	546120	71	363	1	50
143	72	4	2	38	96840	72	5	5	32
144	72	5	5	45	2520	72	5	6	27
145	72	5	6	35	1017364	72	17	1	11
146	72	17	6	21	172080	72	19	6	9
147	72	19	6	15	172080	72	21	6	3
148	72	21	6	11	269640	72	24	9	5
149	72	24	9	13	763200	72	33	5	13
150	72	33	5	18	1098360	72	45	22	24
151	72	45	22	32	14040	72	46	2	26
152	72	46	2	34	360	72	46	2	40
153	72	46	2	48	87840	72	47	3	12
154	72	47	5	26	1033920	72	59	4	38
155	72	61	7	8	2160	72	61	7	44
156	72	61	7	52	395280	72	65	21	40
157	72	65	21	48	812520	72	75	7	30

TABLE 2

Summary of Frequency Bands Used to Define the Energy Spectrum

Spectrum Number	Frequency Range (Cycles/hr) (and Period)	Bandwidth Cycles per hour	Degrees of Freedom	98% Confidence Band	
				Upper	Lower
1	5.27 to 1800 (11.4 mins to 2 sec.)	1.76	33775	0.078	-0.078
2	0.176 to 30 (5.68 hrs to 2 mins)	0.058	888	0.49	-0.47
3	0.0439 to 30 (22.78 hrs to 2 mins)	0.0146	132	1.32	-1.18
4	0.0018 to 5 (22.7 days to 12 mins)	0.00061	12	5.13	-3.49

TABLE 3

Statistics of the Wind Speed Classified According to Time of Day and Month of Year

Time of Day E.S.T.	March 1971				April 1971			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	3.5	1.88	2.01	2.41	3.8	2.29	1.91	-2.32
13-16	4.1	1.81	2.07	2.46	3.8	1.95	1.85	-2.26
16-19	3.1	1.58	1.98	2.35	3.0	1.88	1.75	-2.13
19-22	2.3	1.53	1.70	2.10	2.4	1.52	1.86	-2.22
22-01	1.8	1.10	1.69	2.08	2.3	1.55	1.87	-2.23
01-04	1.8	1.11	1.65	2.02	2.2	1.44	1.88	-2.25
04-07	2.0	1.47	1.86	2.27	2.2	1.46	1.90	-2.26
07-10	2.9	1.69	2.05	2.45	2.9	2.10	1.88	-2.27

Time of Day E.S.T.	May 1971				June 1971			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	4.0	1.87	1.73	2.15	3.2	1.92	1.84	-2.25
13-16	4.0	1.43	1.65	2.07	2.9	1.98	1.58	-2.00
16-19	3.0	1.90	1.74	2.13	2.2	1.80	1.95	-2.35
19-22	2.1	2.07	1.89	2.32	2.2	1.57	1.93	-2.35
22-01	1.9	1.85	1.94	2.34	2.4	1.58	1.83	-2.22
01-04	2.6	1.80	1.83	2.22	2.2	1.46	1.73	-2.13
04-07	2.7	1.92	1.68	2.05	2.3	1.68	1.93	-2.31
07-10	2.9	1.93	1.64	2.03	2.8	1.89	2.00	-2.38

Time of Day E.S.T.	July 1971				August 1971			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	3.3	2.09	1.82	2.25	4.7	2.41	1.73	-2.16
13-16	3.5	1.98	1.83	2.26	4.3	2.34	1.71	-2.16
16-19	2.6	1.75	1.81	2.18	3.2	1.78	1.89	-2.29
19-22	2.3	1.53	1.78	2.15	3.0	1.75	1.92	-2.31
22-01	2.4	1.45	1.83	2.22	3.1	2.06	1.92	-2.32
01-04	2.3	1.58	1.83	2.19	3.3	2.16	1.96	-2.35
04-07	2.5	1.69	1.88	2.25	3.6	2.10	1.91	-2.30
07-10	2.7	1.69	1.85	2.24	4.0	2.36	1.79	-2.21

TABLE 3—[Continued]

Time of Day E.S.T.	September 1971				October 1971			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	5.0	2.66	1.80	-2.24	6.3	3.01	1.59	-2.03
13-16	4.6	2.78	1.72	-2.16	6.1	3.14	1.47	-1.94
16-19	3.1	2.08	1.75	-2.17	5.0	2.88	1.62	-2.07
19-22	2.8	1.91	1.77	-2.20	3.6	2.23	1.70	-2.08
22-01	2.8	2.14	1.94	-2.34	3.1	2.07	1.66	-2.06
01-04	2.8	2.22	1.93	-2.33	3.2	2.04	1.63	-2.01
04-07	3.0	2.13	1.88	-2.28	3.5	1.90	1.68	-2.07
07-10	4.2	2.81	1.84	-2.27	5.2	2.44	1.67	-2.09

Time of Day E.S.T.	November 1971				December 1971			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	5.5	2.59	1.93	-2.38	3.9	2.23	1.84	-2.28
13-16	5.9	2.43	2.08	-2.52	4.5	2.22	1.96	-2.38
16-19	4.9	2.51	1.94	-2.35	4.3	2.03	1.91	-2.34
19-22	3.8	2.82	1.76	-2.19	3.6	1.95	1.81	-2.26
22-01	3.3	2.40	1.66	-2.09	2.8	1.86	1.78	-2.21
01-04	3.0	2.30	1.76	-2.21	2.6	1.98	1.75	-2.18
04-07	3.2	2.37	1.66	-2.09	2.4	1.72	1.69	-2.13
07-10	4.4	2.82	1.81	-2.24	3.3	2.00	1.87	-2.30

Time of Day E.S.T.	January 1972				February 1972			
	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$	Wind Speed		Log n_m	Log $\frac{P(n_m)}{\sigma^2}$
	Mean	S.D.			Mean	S.D.		
10-13	3.6	2.24	1.92	-2.33	4.2	2.06	1.82	-2.28
13-16	4.5	2.19	2.05	-2.44	4.1	2.18	1.94	-2.39
16-19	4.3	2.21	2.06	-2.47	3.7	2.06	1.95	-2.39
19-22	3.1	2.09	2.07	-2.48	3.0	1.77	1.79	-2.26
22-01	2.6	1.91	2.09	-2.49	2.5	1.61	1.60	-2.02
01-04	2.1	1.66	1.92	-2.34	2.1	1.43	1.52	-1.92
04-07	2.0	1.64	1.82	-2.25	2.5	1.62	1.68	-2.10
07-10	2.3	1.86	1.77	-2.21	3.8	2.16	1.79	-2.25

TABLE 4

Distribution of 1-second Average Wind Speeds and Upcrossings of Upper Level of Class

Wind Speed Band m/sec	Number of Occurrences	Number of Upcrossings of Upper Level	Wind Speed Band m/sec	Number of Occurrences	Number of Upcrossing of Upper Level
0-0	113 455	13 876	13-19-13-74	16 401	12 848
0-01-0-55	946 911	76 729	13-74-14-29	11 689	9 308
0-55-1-10	3 024 694	253 845	14-29-14-84	8 332	6 615
1-10-1-65	3 988 513	396 141	14-84-15-38	5 624	4 642
1-65-2-20	3 511 389	496 461	15-38-15-93	3 954	3 221
2-20-2-75	3 019 753	581 836	15-93-16-48	2 721	2 198
2-75-3-30	2 673 084	644 758	16-48-17-03	1 759	1 462
3-30-3-85	2 351 405	664 664	17-03-17-58	1 227	976
3-85-4-40	2 015 273	649 922	17-58-18-13	795	654
4-40-4-95	1 711 247	608 582	18-13-18-68	510	424
4-95-5-49	1 404 397	545 918	18-68-19-23	334	251
5-49-6-04	1 122 307	473 159	19-23-19-78	205	143
6-04-6-59	883 835	399 155	19-78-20-33	108	94
6-59-7-14	687 300	327 943	20-33-20-88	64	69
7-14-7-69	522 083	264 393	20-88-21-43	49	49
7-69-8-24	393 187	209 813	21-43-21-98	33	36
8-24-8-79	294 490	164 145	21-98-22-53	22	23
8-79-9-34	218 487	126 919	22-53-23-08	24	14
9-34-9-89	159 779	97 087	23-08-23-63	7	10
9-89-10-44	115 395	73 752	23-63-24-18	7	8
10-44-10-99	83 704	55 817	24-18-24-73	5	6
10-99-11-54	60 615	41 935	24-73-25-27	3	4
11-54-12-09	43 806	31 543	25-27-25-82	1	3
12-09-12-64	31 597	23 745	25-82-26-37	3	0
12-64-13-19	22 913	17 372	26-37-26-92	0	0

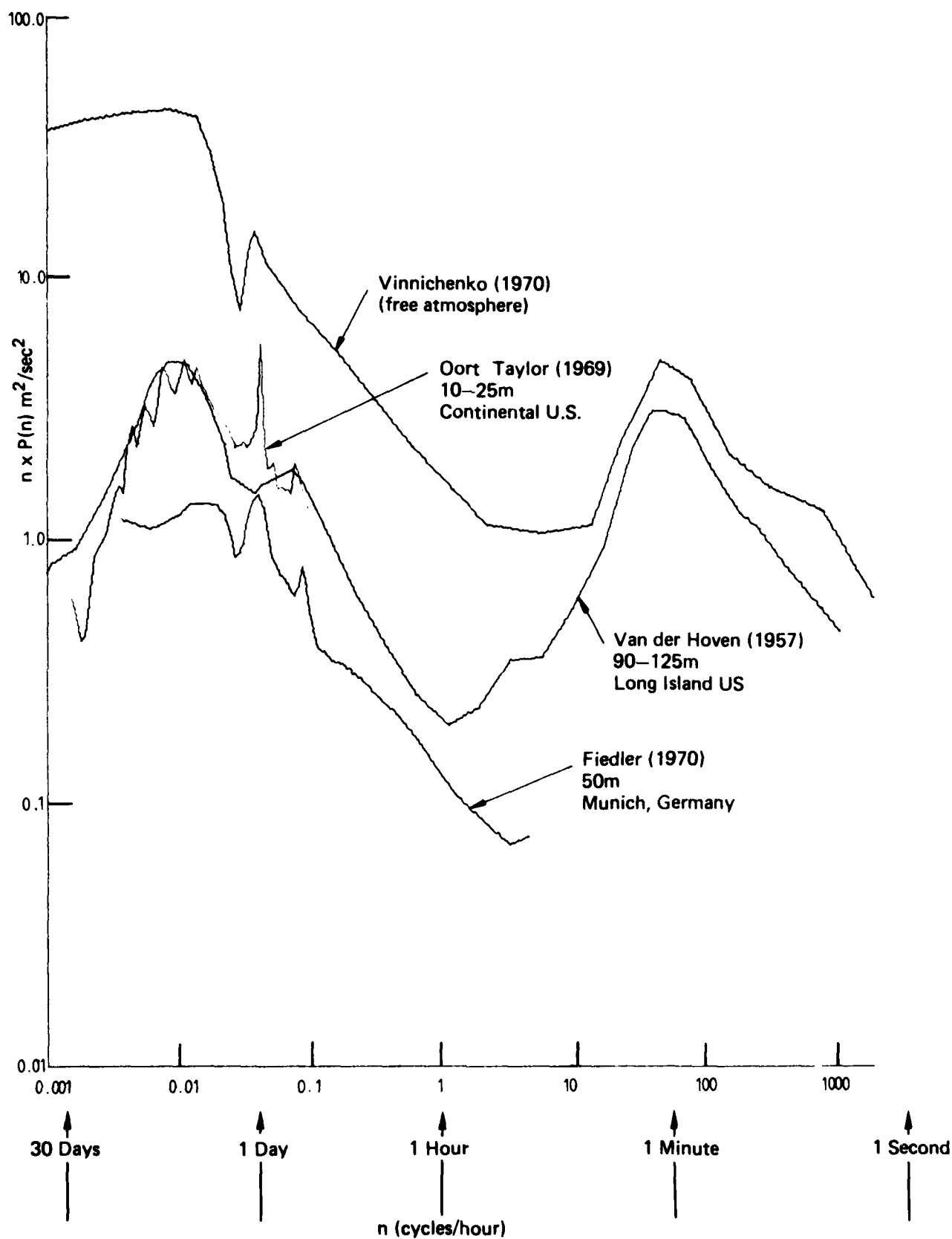


FIG. 1 FOUR DIFFERENT MEASUREMENTS OF THE WIND SPEED POWER SPECTRUM

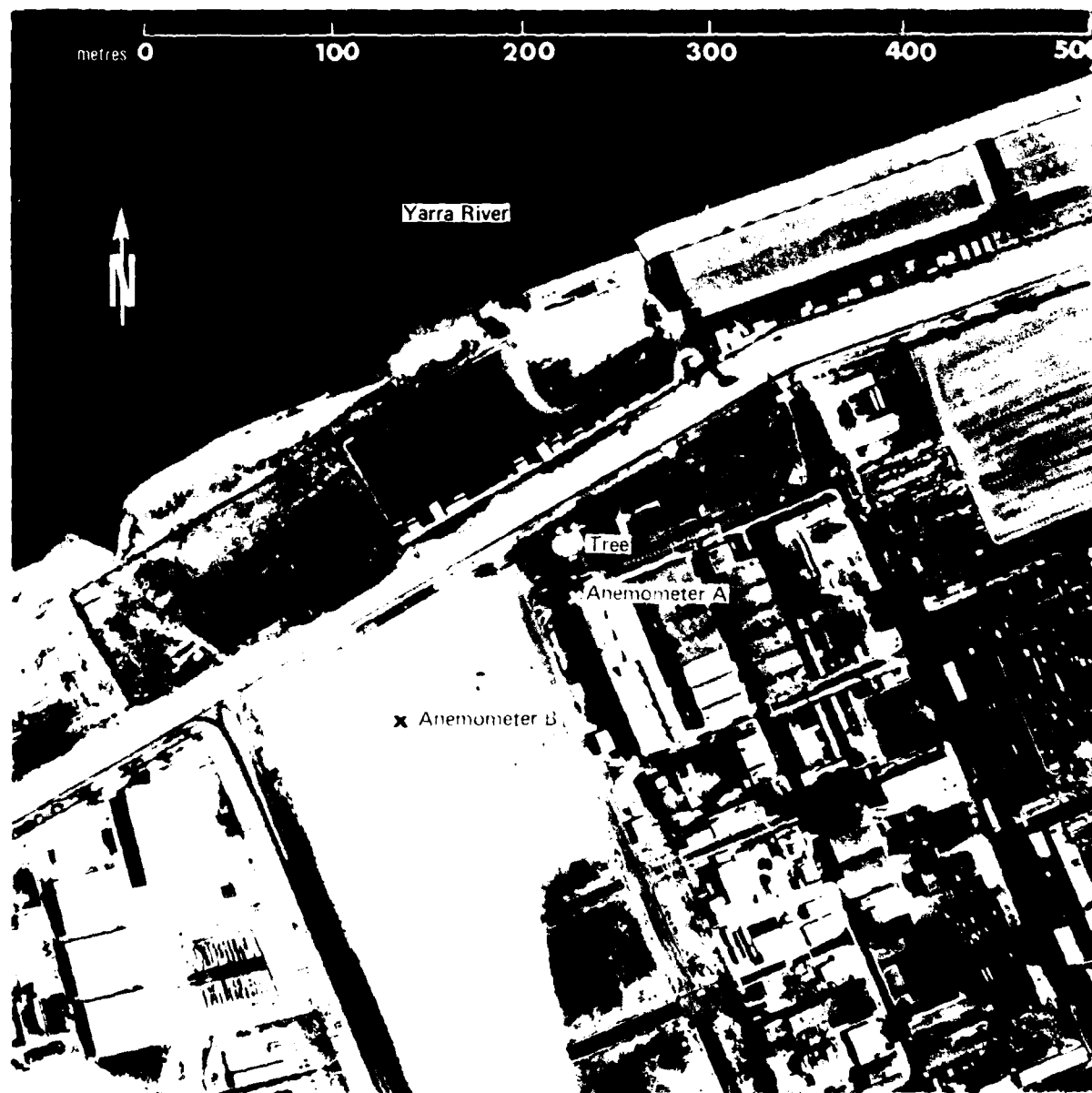


FIG. 2 AERIAL PHOTOGRAPH OF THE AERONAUTICAL RESEARCH LABORATORIES & SURROUNDINGS.

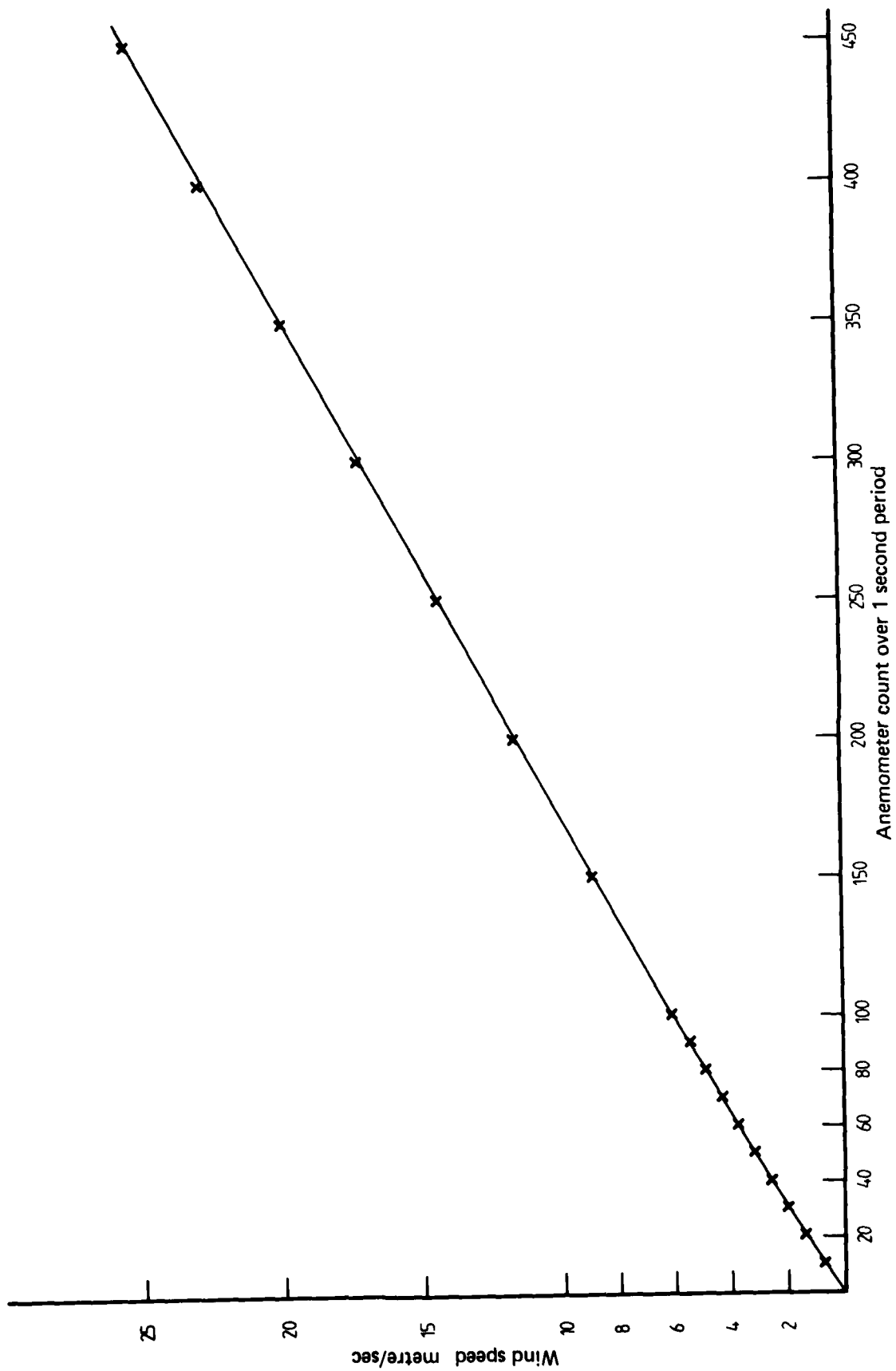


FIG. 3 CALIBRATION CURVE FOR ANEMOMETER 'A'

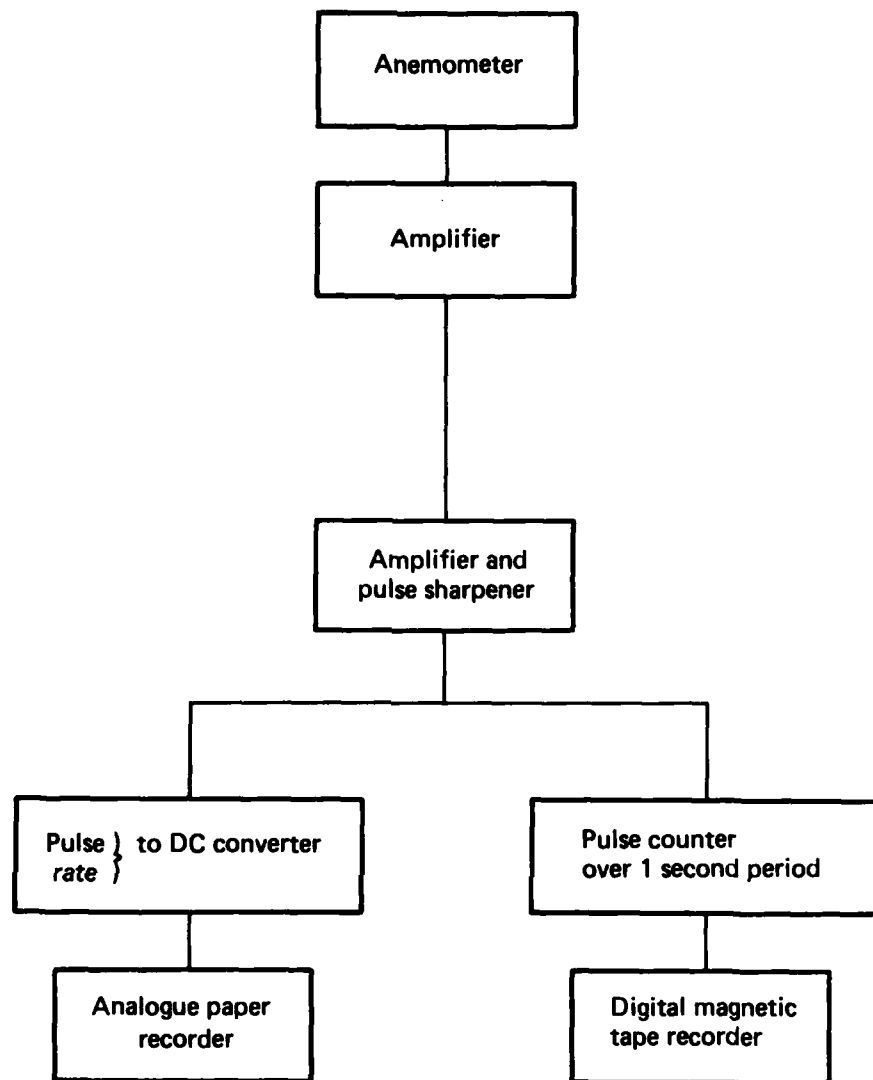


FIG. 4 SCHEMATIC OF RECORDING SYSTEM

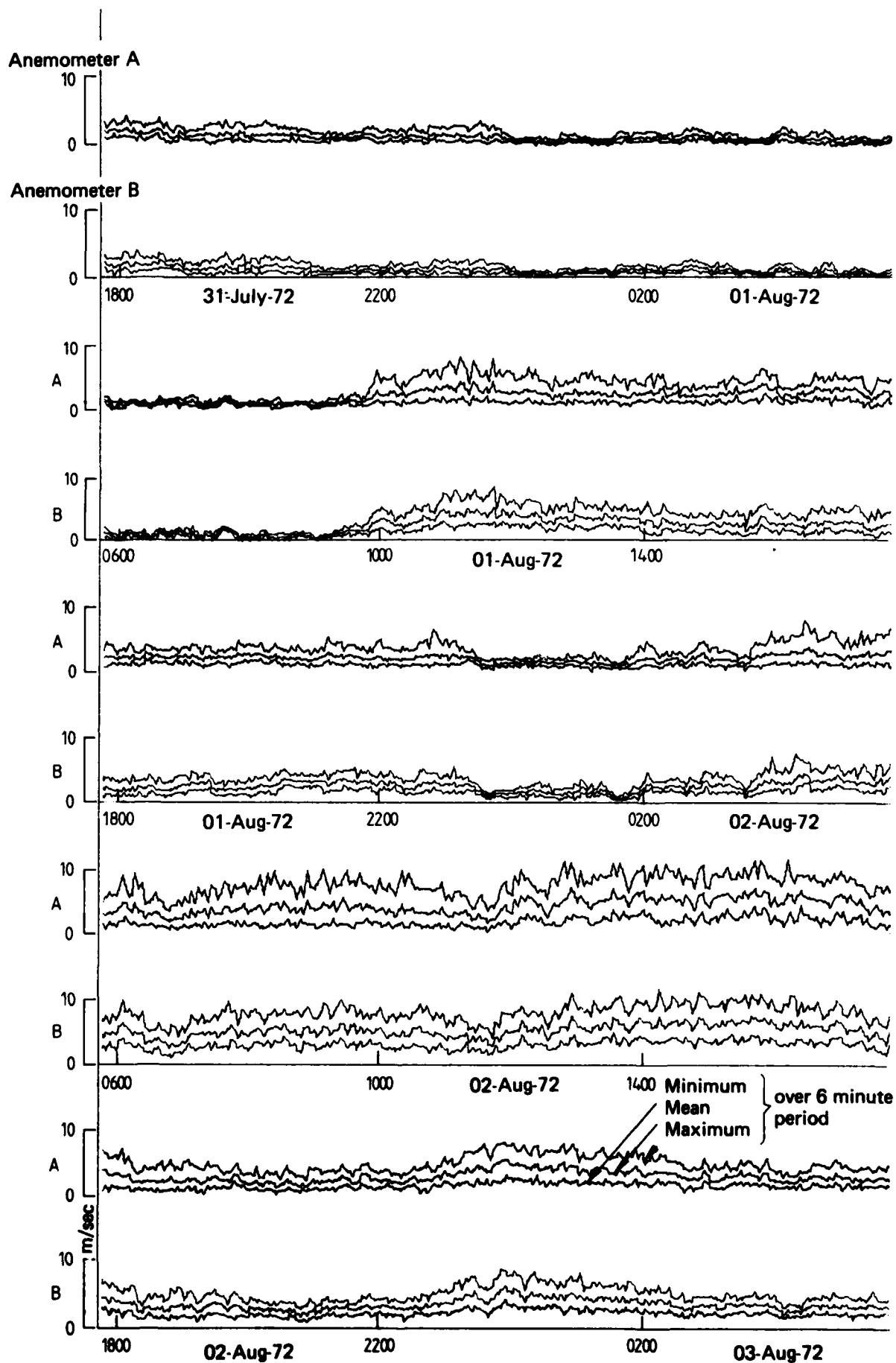


FIG. 5 ERROR CHECKING PLOT - A SAMPLE PLOT OF 6 MINUTE MEANS, MINIMA AND MAXIMA OF THE WIND SPEED

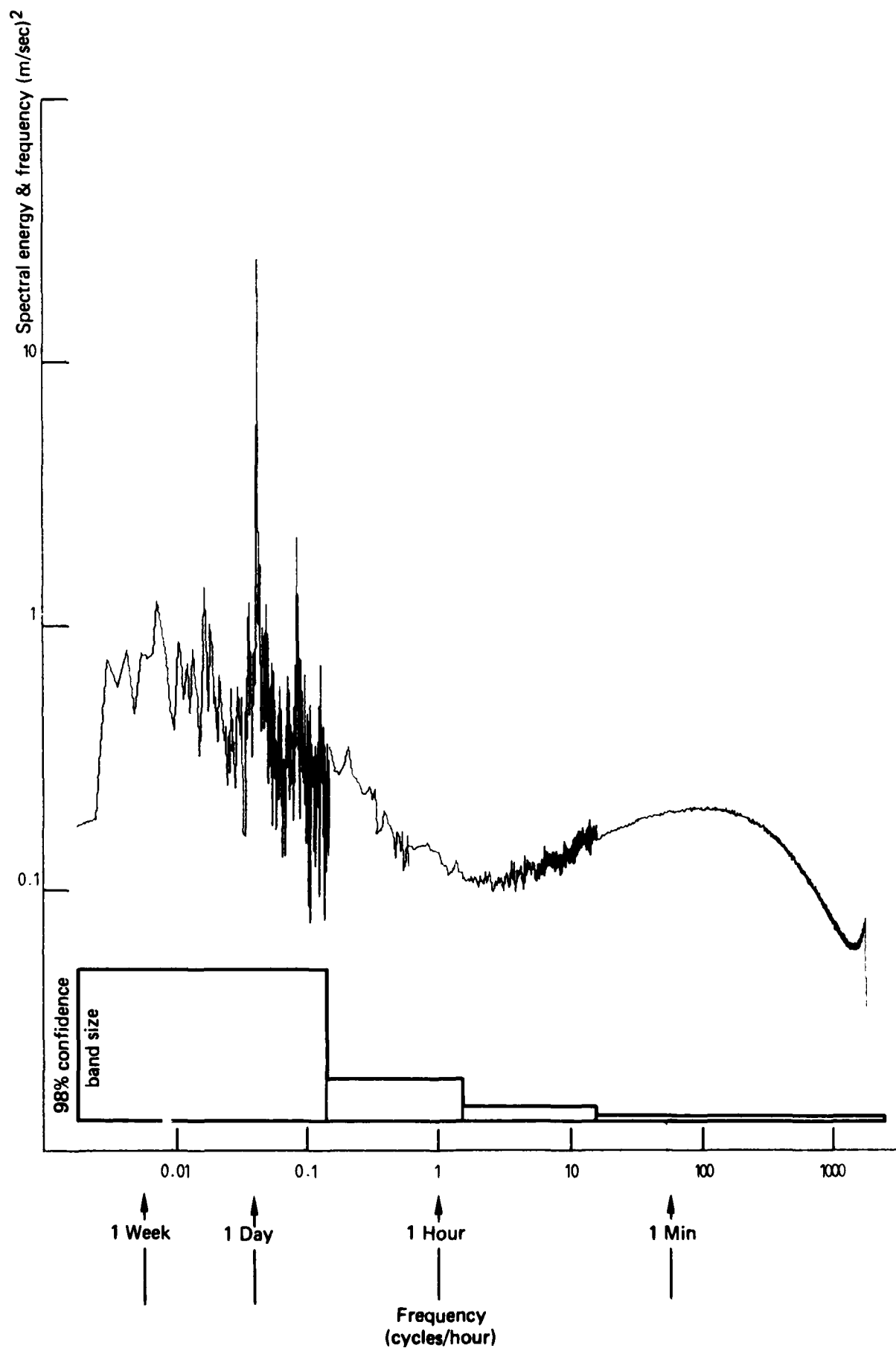


FIG. 6 ENERGY SPECTRUM OF THE WIND SPEED

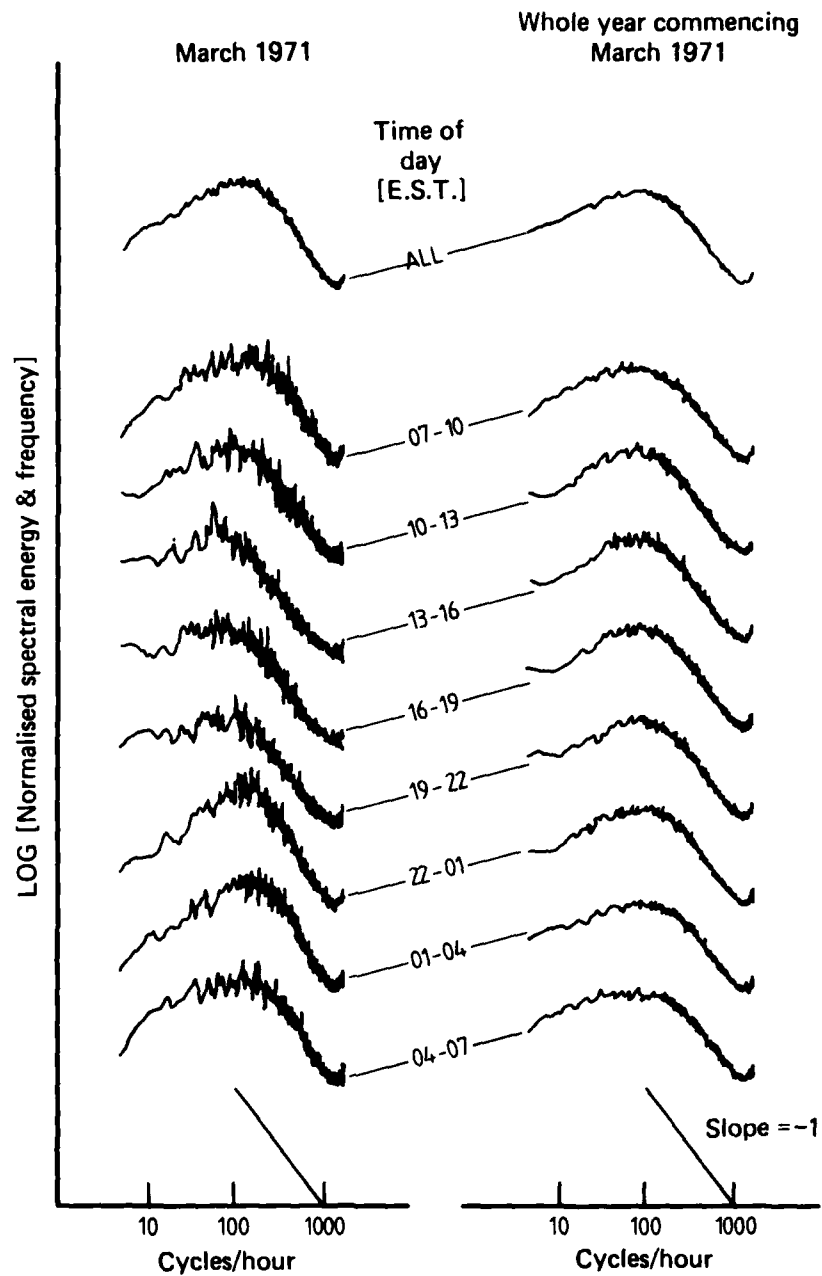


FIG. 7 VARIATION OF THE SHAPE OF THE ENERGY SPECTRA OF WIND SPEED CLASSIFIED BY TIME OF DAY AND MONTH OF YEAR

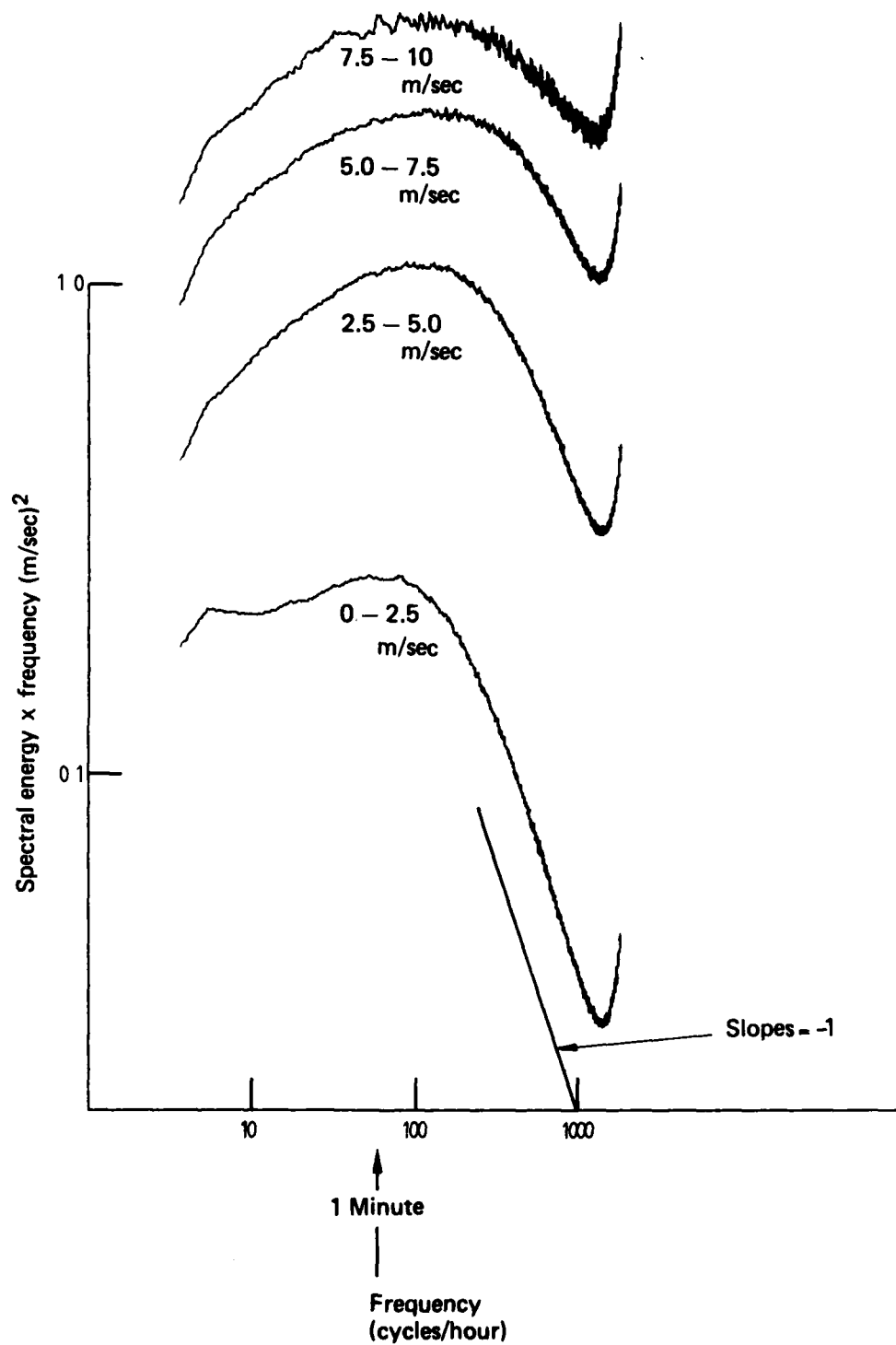


FIG. 8 ENERGY SPECTRA CLASSIFIED BY RANGE OF WIND SPEED

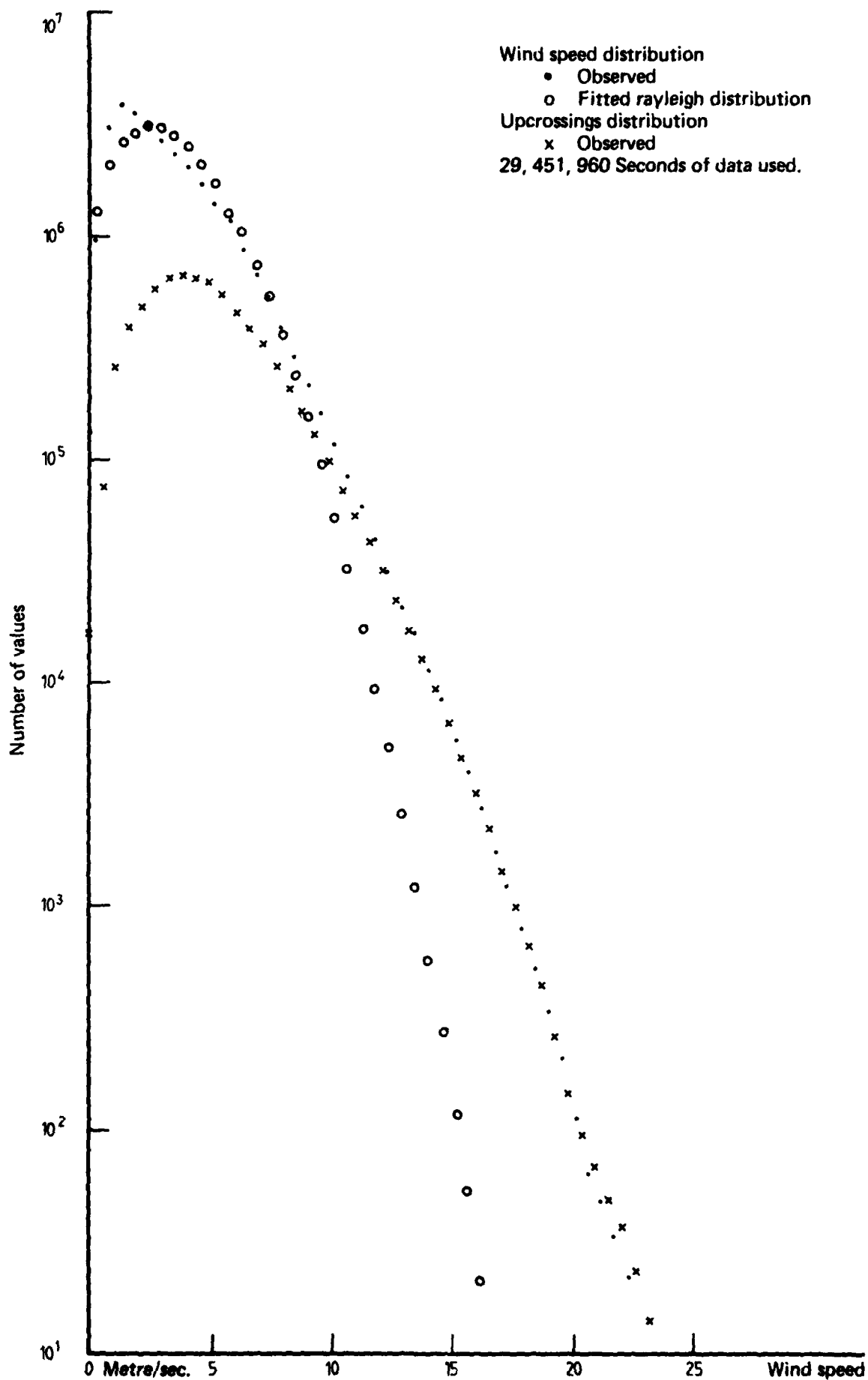


FIG. 9 DISTRIBUTION OF WIND SPEED AND UPCROSSINGS OF VARIOUS WIND SPEED LEVELS

0 represents	100 to	300	occurrences per cell
1 represents	300 to	1,000	" "
2 represents	1,000 to	3,000	" "
3 represents	3,000 to	10,000	" "
4 represents	10,000 to	30,000	" "
5 represents	30,000 to	100,000	" "
6 represents	100,000 to	300,000	" "
7 represents	300,000 to	1,000,000	" "
8 represents	1,000,000 to	3,000,000	" "
9 represents	3,000,000 to	10,000,000	" "

29,450,000 seconds of data used

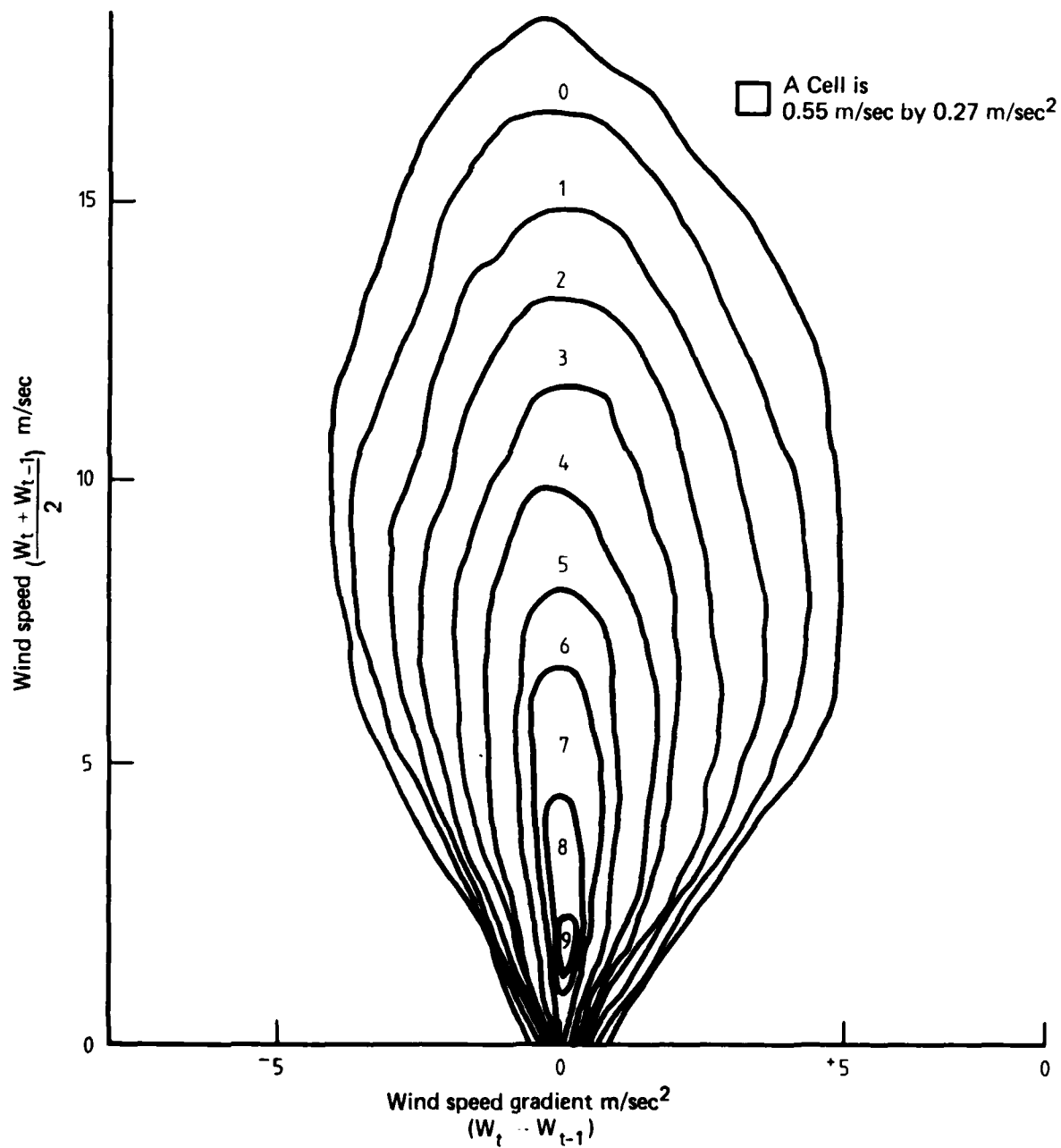


FIG. 10 JOINT DISTRIBUTION OF WIND SPEED AND WIND SPEED GRADIENT

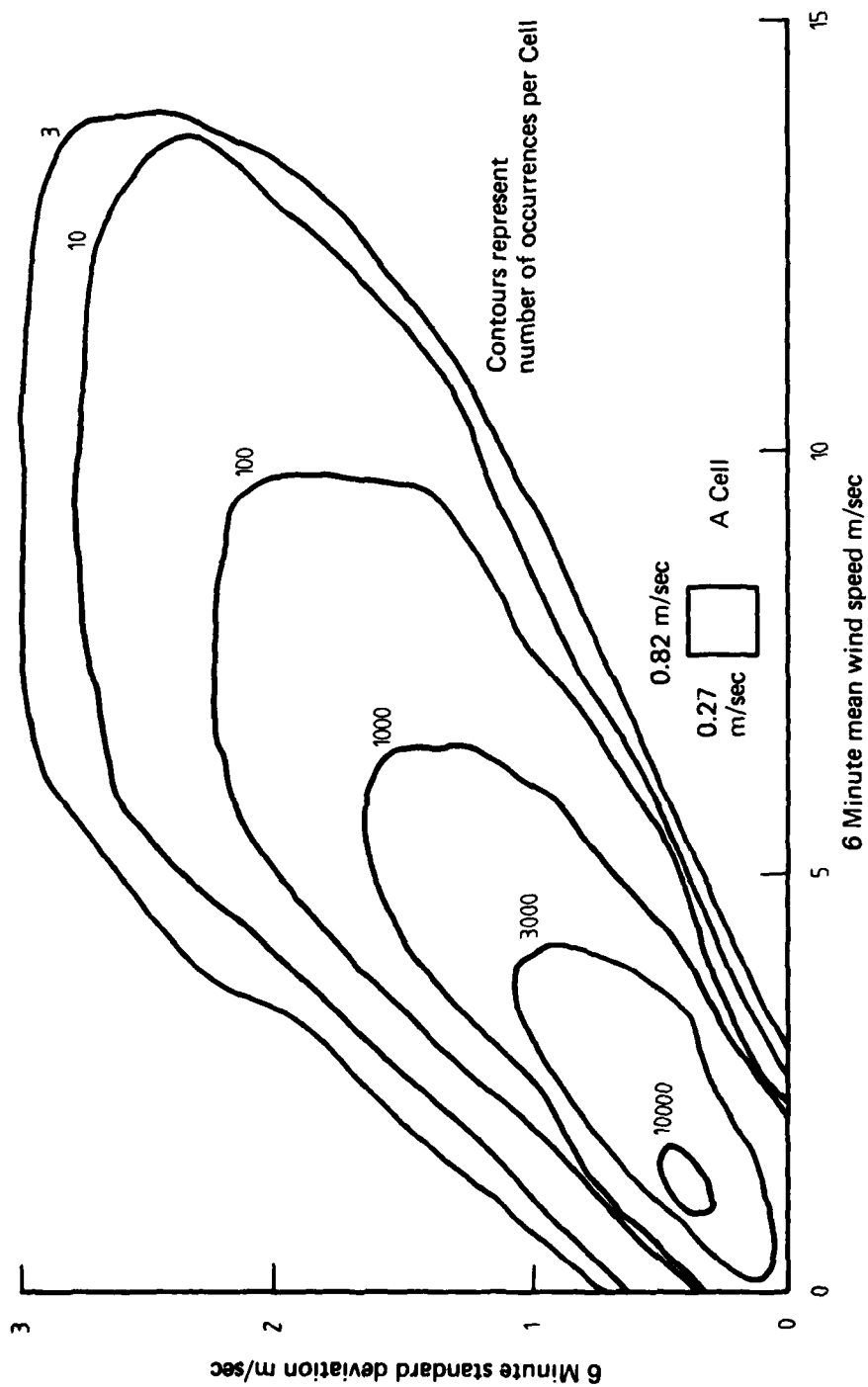


FIG. 11 JOINT DISTRIBUTION OF SIX MINUTE MEANS AND SIX MINUTE STANDARD DEVIATIONS OF WIND SPEED

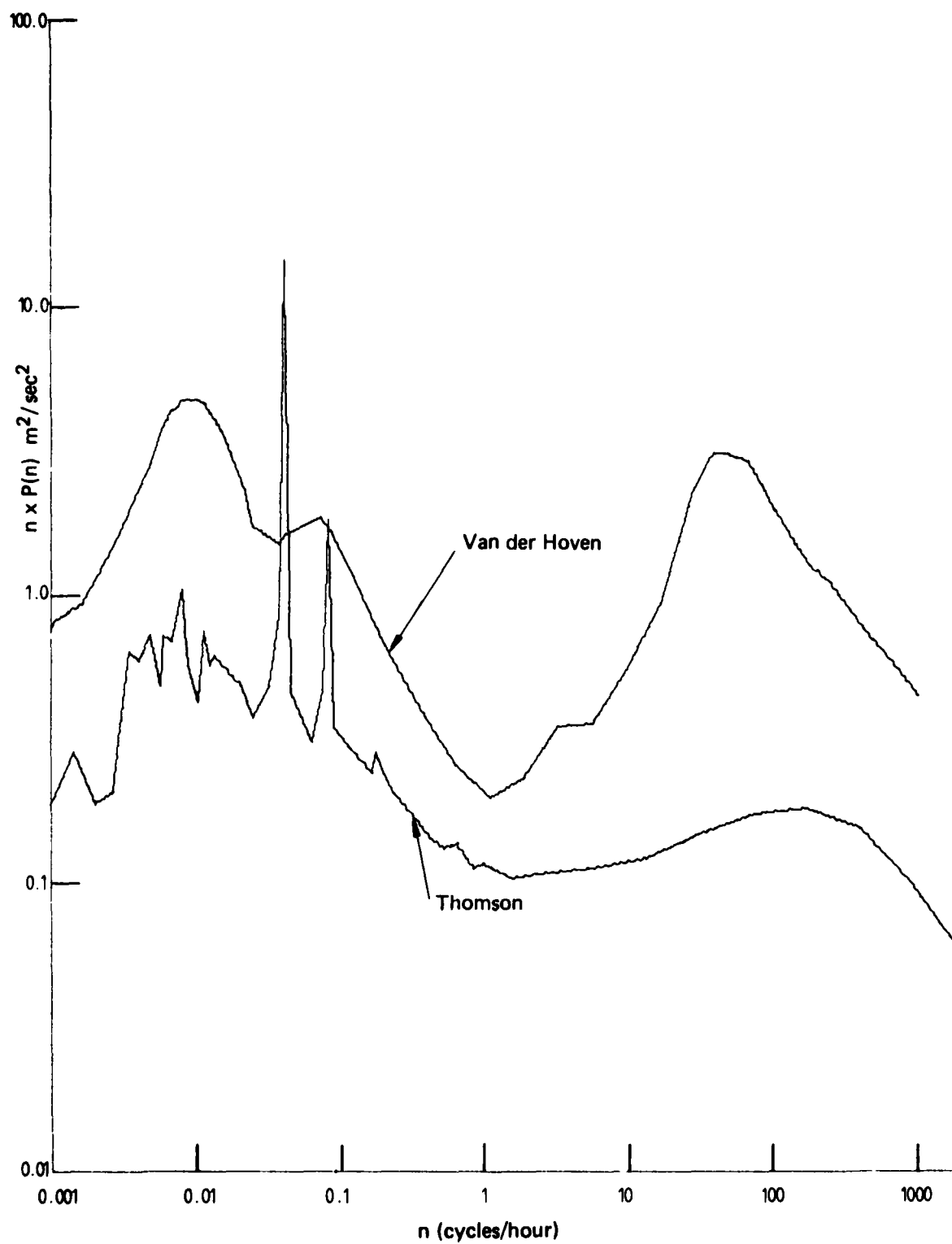


FIG. 12 COMPARISON OF WIND POWER SPECTRA

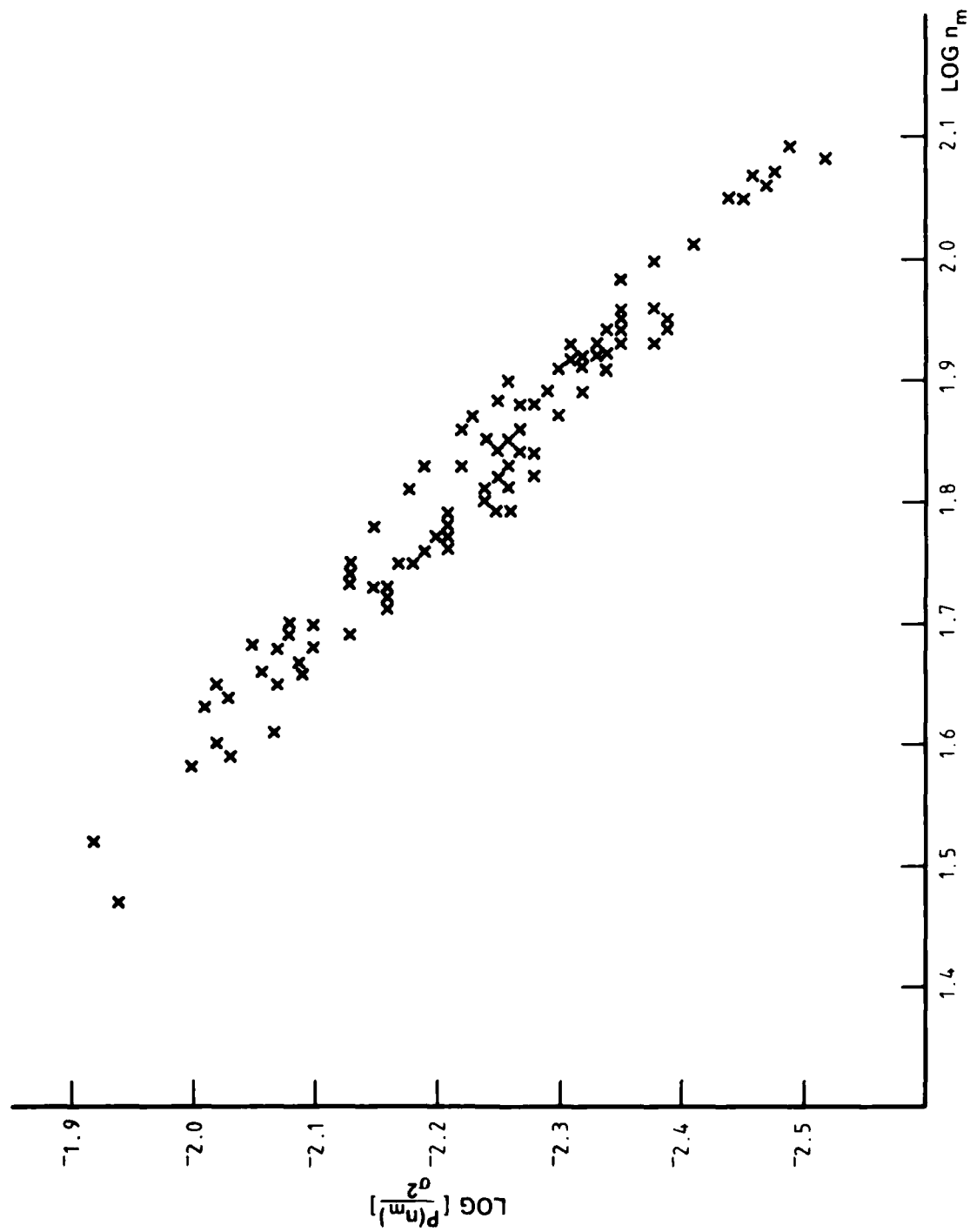


FIG. 13 PEAK FREQUENCY VERSUS PEAK SPECTRAL POWER FOR THE 96
TIME OF DAY, MONTH OF YEAR COMBINATIONS

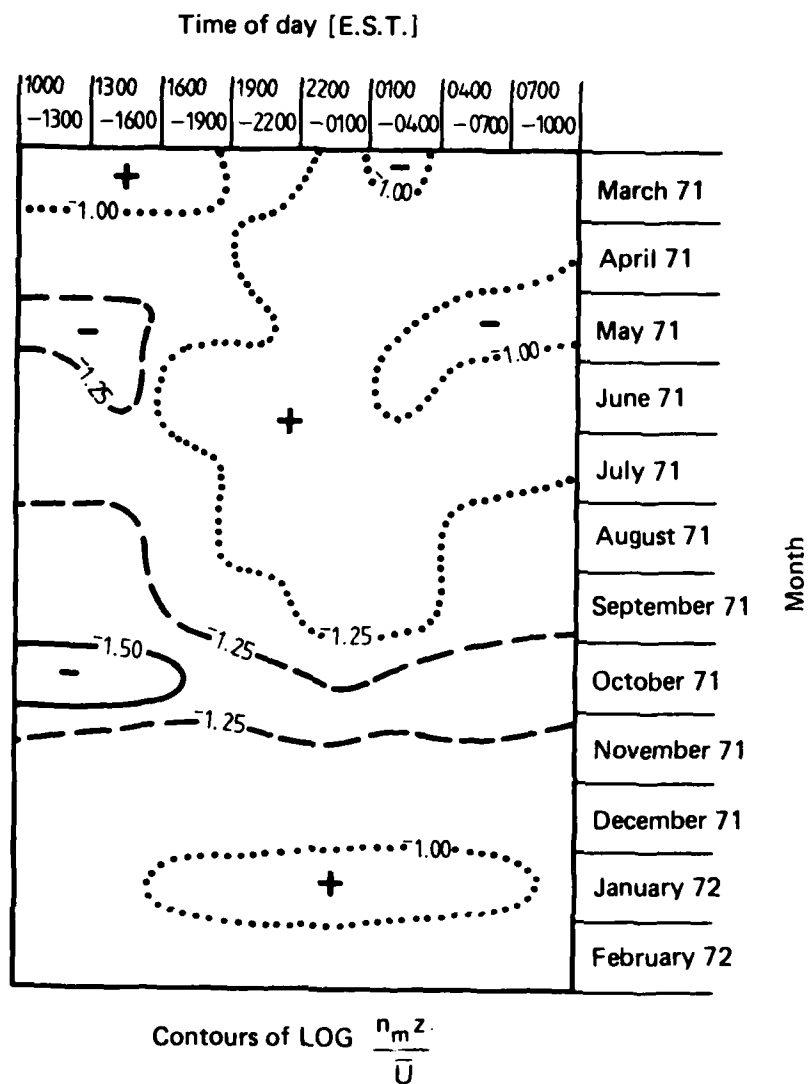


FIG. 14 VARIATIONS OF FREQUENCY OF PEAK SPECTRAL ORDINATE THROUGHOUT THE YEAR

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